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Opportunities for Irradiation Studies of Structural Materials for Neutron Sources at the Proton Beam-Stop of Moscow Meson Factory

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Abstract

In order to be able to investigate experimentally the effect of simultaneous irradiation and stress on solid-liquid metal reactions at widely different temperatures, a modification to the existing irradiation facility at the beam stop of the Moscow Meson Factory (MMF) is examined. The facility would allow to irradiate tubular specimens under internal pressure in a liquid metal environment. Even at its current performance level (50 μA at 500 MeV) the proton beam intensity is sufficient to generate in a suitably large spot peak power densities in the specimens that correspond to the highest loads anticipated in spallation targets currently under study. The installation could be realised in such a way that use can be made of existing equipment both at MMF and nearby laboratories that operate hot cells. Particular attention is being paid to safe and simple handling operations when replacing the specimens and preparing them for shipment.

1. Introduction

Structural materials of neutron sources are subject to a number of load factors, which are known to give rise to the temporal degradation of materials properties. This includes variable internal and external stresses caused by mechanical loads and temperature gradients, structural changes under proton and neutron irradiation of high intensity and corrosion effects. In the case of liquid metal cooling also surface interactions with liquid metals and related phenomena [1] may play a role.

In view of the very limited information available on liquid metal - solid metal interactions in a radiation environment, studying these effects has become particularly important because of increasing R&D activities world wide in related fields such as:

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- targets for a new generation of high intensity proton accelerators (for neutron sources, electronuclear and transmutation facilities with use of lead-bismuth, mercury or gallium in the liquid state [2-13]);
- materials for fusion reactors (questions of the first wall and blanket cooling by lithium, lithium-lead and gallium [14]);
- fast sodium-cooled reactors [15];
- safe power and transport reactors of a new generation with liquid lead and lead-bismuth as coolants [16,17];.

The above mentioned factors may significantly influence the processes of vacancy void swelling, radiation embrittlement and cracking of materials. Liquid metals, through the Rebinder effect [1,18], may reduce the strength (toughness) of materials and give rise to erosion and various kinds of corrosion [1,18,19,20]. A number of other concomitant factors exist [19,20], which defy theoretical or numerical analysis because of the complexity of the problem. In this situation experimental testing is important, and a special experimental facility that allows to investigate all the relevant factors and their complex interaction is highly desirable.

A particular task of near term importance is the experimental assessment of anticipated lifetimes for target windows of high current proton accelerators and the related verification of basic engineering solutions, because several such systems are imminent [2-7].

For this purpose, a special installation based on the beam-stop of the Moscow Meson Factory is proposed. A schematic of the current design of this beam stop is presented in Fig. 1a [21]. The installation consists of a water cooled thermal shield, an aluminium alloy body, a cassette with tungsten plates and the upper plug with channels for coolant (water). It is equipped with a water cooled insert for irradiation of samples in mixed proton and spallation neutron fields. In the present paper possible modifications to this installation are considered which would make it suitable for irradiating specimens under stress and in contact with liquid metals. The necessary requirements and conditions for such irradiation experiments are discussed and it will be shown that appropriate conditions can be generated at the facility.

2. Requirements to the proton beam, the irradiated samples and the installation

2.1 Load levels

The facility should allow to subject the samples to the following load levels:

- continuous mechanical pressure of 0.3 – 2.0 MPa,
- liquid metal at temperatures of 100 – 250°C (Hg), 150 – 400°C (Pb-Bi), 500 – 600°C (Na, Pb);
- heat release density in a steel sample not less than 1.5 10^9 W/m^3. (This heat release density corresponds to the expected thermal loading in materials of neutron target windows for high

current proton accelerators like SNS or ESS and will be sufficient also for the study of structural materials for fission and fusion nuclear reactors.)

2.2 Beam conditions and power deposition

The high intensity linear proton accelerator of the Moscow Meson Factory (Institute for Nuclear Research, RAS) is designed for 600 MeV proton beam energy and a current of 500 μA. Presently a proton current of 70 μA at an energy of 500 MeV is available.

For a Gaussian current density distribution in the beam the power density in the specimens can be represented as::

$$q_v(r) \cong k\rho \frac{dE}{d(\rho x)} \cdot \frac{J_0}{2\pi\sigma^2} \exp\left(-\frac{r^2}{2\sigma^2}\right) = q_{v\max} \cdot \exp\left(-\frac{r^2}{2\sigma^2}\right), \qquad (1)$$

and the standard deviation of the beam, σ, required to obtain a certain maximum power density $q_{v\max}$ becomes (cf. Fig 2):

$$\sigma = \sqrt{\frac{k\rho J_0}{2\pi q_{v\max}} \cdot \frac{dE}{d(x\rho)}}, \qquad (2)$$

Where, the coefficient k takes into account the excess heat release over ionisation losses due to secondary particles in the cascade-evaporation process and from neutron and γ-absorption. This coefficient may be in the range from 1.2 to 1.4 depending on the energy of the primary proton beam, materials used and the design of the target. ρ is the density of the material; $dE/d(x\rho)$ represents the linear ionisation losses.

According to equ. (2), even for a current of 50 μA, the radius of the irradiated area which contains 40% of the proton beam current is equal to $r = \sigma \cong 3.5$ mm. Such dimension is acceptable for physical and mechanical studies.

The radiation damage in steel generated by this beam was estimated and is shown as a function of beam diameter in Fig.3. For a current of 50 μA with σ of 3.5 mm we expect about $1.2\text{x}10^{-6}$ dpa/s, i.e. roughly 0.1 dpa/day.

2.3 Test specimens

For testing of reactor materials under the influence of pressure, tubular samples are used (Fig. 4a). They have diameters of 0.5 – 2 cm and thickness 0.3 - 0.5 mm and are filled with argon at 15 – 20 MPa. This provides a relatively simple way of subjecting the specimens to tensile stress during irradiation. The irradiated samples are cut into ringlets with a height of 4 – 5 mm for physical studies and mechanical testing (Fig. 4b). A suitable specimen holder for tensile testing is shown in Fig 4d.

Reactor irradiation provides uniform radiation damage in tubular samples with a height of about of 0.1 m. If the same method is to be used in proton irradiation experiments, it is necessary to fix exactly the orientation of samples during physical investigations because of the small area of the proton spot (8 – 20 mm in diameter for currents of 50 – 500 μA). So, initial marking of the samples and corresponding positioning in post-irradiation studies is necessary (Fig. 4a and d).

The tubular samples may be naturally put together as hexagonal or cylindrical assembly similar to fuel elements of nuclear reactors (Fig. 4c). The hydrodynamics and heat transfer for such an assembly are well understood, including critical parameters [22,23]. Moreover, the assembly cover may be used as reference sample irradiated without mechanical stresses.

For other existing methods of testing under stress it would be more difficult to maintain a continuous mechanical load under irradiation (cf. also section 5). This would require additional equipment and will therefore be only considered if there is a sufficiently strong case for it.

2.4 Requirements to the irradiation rig

The proposed layout of the installation takes into account the following requirements:

- a reasonably simple and quick change of samples;
- precise control of the beam position;
- power density of the order of 1.5×10^9 W/m^3 as anticipated e.g. for the ESS beam window [4,7];
- control and stabilisation of temperature;
- an external liquid metal coolant for heat transfer;
- height limitations of the liquid metal insert and sample holders as imposed by the hot cell facilities to be used for post irradiation examination, in case the whole insert has to be taken into a hot cell[1];
- a minimum amount of a liquid metal, especially in the case of mercury or sodium;
- a conversion of radioactive mercury after the experiment into solid solutions (Pb-Hg, Cu-Hg) or complexes like Hg_2Cl_2 in the device for easier handling and waste management.

A double walled stainless steel container with the interspace filled with argon will be provided in order to ease control of the temperature in the liquid metal and for safety. Argon is chosen because helium can easily escape through micro-cracks in welded joints. The space between the container walls will be controlled for leakage.

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[1] It would be possible to utilise the existing technology and equipment of laboratories of SSC IPPE, RFC Kurchatov Institute, and Institute of Atomic Reactors (RIAR), thereby avoiding significant expenses that might have to be faced if PIE was carried out abroad.

3. Basic layout of the installation

3.1 Overall Design

The dimensions given below for some of the components are for a beam current of 50 μA as presently available. They may be increased as higher currents become available to irradiate more or larger specimens at the same current density.

For the liquid metal irradiation experiment most of the existing outer plug of the beam stop of the Moscow Meson Factory (Fig. 1a), including the water cooled stainless steel thimble for the irradiation insert will remain essentially unchanged, with possibly minor modifications to accommodate the new liquid metal irradiation insert (Fig. 1a and 5). This will be a double walled stainless steel container which will be inserted into the water cooled aluminum thimble inside the tungsten beam stop. The interspace between the two walls will be filed with circulating argon and will be surveyed for leakage from either one of the two walls which will have water on the outside and liquid metal on the inside. Apart from monitoring the pressure and composition of the argon, there will be electrical sensors in the interspace to indicate any ingress of water or liquid metal. The outer diameter of this container will be ≈ 4 cm in the irradiation area and will widen further up. The walls will be about 1 mm thick and will have spacers between them.

The tubular specimens will be arranged in a cassette with a diameter of about 3-4 cm which is suspended from a cylindrical bar and held against a hollow steel cylinder which separates the downward from the upward liquid metal flow. Heaters for temperature control are located at the cylinder surface.

The upper part of the container is surrounded by a magneto-hydrodynamic (MHD) induction pump. This pump is designed as a tight stator of an asynchronous motor with a short-circuited rotor and pumps the liquid metal in a spiral channel. Due to the centrifugal effect, the spiral MHD pump gives higher values of pressure than a linear motor at the same energy consumption. For ease of manufacturing the helical flow guides of the pump are assumed to be attached to the inner cylinder, although it might be preferable to have them fixed to the container for tightness. The liquid metal will be pumped downwards in the annulus between the cylindrical insert and the inner container wall and will rise between the specimens in the cassette and through the bore in the cylinder. Above the level of the pump the liquid metal flows from inside the cylinder to the outside through bores. A free surface is maintained with a gas atmosphere above it.

The upper part of the container will be an expandable bellows in order to be able to raise the whole assembly of the inner cylinder and the specimen cassette above the level of the liquid metal (which then collects in the bottom of the container) without having to open the system at that stage (see section 4).

Transverse dimensions of the installation in its upper part will be determined by different boundary conditions, such as standard tube diameters and the internal diameter of a suitable stator of a standard asynchronous electrical motor. Such values as clearances for liquid metal passage and height of the pump stator remain to be determined in alloy body, tungsten plates that would be behind the liquid metal insertion for full stop of the optimisation calculations. Anyhow, the height of the insert should not exceed the limitations imposed by the dimensions of available hot cells and the elements of the existing tungsten beam-stops (aluminium proton beam).

There is no system foreseen for coolant purification, because the irradiation times are sufficiently short (3-6 months). This simplifies the design and operation of the installation.

As a whole, the technical and design solutions chosen satisfy the requirements listed above. Some other important features are:

- The amount of water in the beam is minimised which keeps the radioactivity in the cooling loops low and avoids uptake of hydrogen by the samples in the form of secondary protons that are created in the water coolant by the high current proton beam;
- A large temperature difference can be supported between the liquid metal in the ampoule interior and the water coolant in contact with the external surface of the ampoule;
- The possibility exists to ensure sufficient cooling of proton beam windows by a jet system (see 3.2.2);
- Mostly axis-symmetric parts are used, which simplifies fabrication of the liquid metal insert and the control of the process;
- Existing external parts of the beam-stop that are made of aluminium alloy and the cassette with tungsten plates can be used with minimum changes (the shield plug above the cassette would be fabricated newly, as it completely changes in shape due to MHD pump and supply and control lines);
- The MHD pump that is fabricated on the basis of a serial industrial motor can be reused repeatedly with new cylindrical inserts for different experiments.

3.2 Some detailed considerations

While the whole liquid metal irradiation facility is still in a very conceptual stage of design we would like to give a few details to show that the concept is technically feasible.

3.2.1 The liquid metal pump and loop

As a whole, the design scheme of the liquid metal irradiation insert is similar to the scheme of rotary induction pump and existing designing experience may be used. An available electric rotary pump in Russia is the VIN-5/1.5 [24], it is used in the system of sodium coolant loading in BOR-60 reactor. The pump has an external diameter of 260 mm and can produce a pressure rise of ~ 0.5 MPa at the nominal flow of 1.5 m^3/h. These parameters make available a liquid metal flow of ~1m/s for window and sample cooling. To optimise the coolant flow near the window and keep hydraulic losses along the liquid metal path low, local narrowing of the flow cross section should be provided for near the window. According to one-dimensional estimates, the final pressure gradient along the path will not exceed ~ 0.1 MPa. The pump efficiency will depend, in the first place, on the dimension and shape of the gap between the stator and the liquid metal layer and on the presence of a core of electrotechnical steel in the inner cylinder. It is expected to be of the order of 3-8%. The electrical power consumption of the pump will be 3 - 4 kW, which is to be compared to the heat release in the proton beam-stop of 22.5 – 30 kW (for 450 – 600 MeV and 50 μA).

During the pre-irradiation tests dependencies of velocities and liquid metal flow rate on the electrical power of the pump should be measured. Without irradiation the flow rate can be obtained from the measured temperature rise upon passage of the fluid through the pump and its power consumption (heat input). At low and moderately high temperatures also the contact-free ultrasonic technique developed at PSI [25] can be used for calibration. For this purpose, a test section with a well defined liquid metal layer of about 8 to 10 mm thickness would be employed.

3.2.2 Cooling of the beam windows

In terms of operational safety the most critical point is the window, i.e. the position where the proton beam enters into the irradiation insert, which has the highest heat load and most be cooled very efficiently.

The temperature gradient across the wall at the maximum of heat release, taking into account transverse heat conduction in the wall material, was estimated by using the following expression:

$$q_{s\max} = -\lambda \frac{\partial T(0,\delta)}{\partial z} = 2q_{v\max}\delta \sum_{k=1}^{\infty} \frac{\sin^2(\gamma_k\delta)\cdot\eta_k \exp(\eta_k)E_1(\eta_k)}{\left(1+\frac{Bi}{Bi^2+(\gamma_k\delta)^2}\right)(\gamma_k\delta)^2} \qquad (3)$$

$$T(0,\delta)-\vec{t}_f = \frac{q_{s\max}}{\alpha} = \frac{2q_{v\max}\delta^2}{\lambda} \sum_{k=1}^{\infty} \frac{\sin(\gamma_k\delta)\cos(\gamma_k\delta)\cdot\eta_k \exp(\eta_k)E_1(\eta_k)}{\left(1+\frac{Bi}{Bi^2+(\gamma_k\delta)^2}\right)(\gamma_k\delta)_k^3} \qquad (5)$$

$$\Delta T_{\max} = \frac{2q_{v\max}\delta^2}{\lambda} \sum_{k=1}^{\infty} \frac{\sin(\gamma_k\delta)[1-\cos(\gamma_k\delta)]}{\left(1+\frac{Bi}{Bi^2+(\gamma_k\delta)^2}\right)(\gamma_k\delta)^3}\,\eta_k \exp(\eta_k)E_1(\eta_k) \qquad (4)$$

$$\eta_k = \left(\frac{x_k\sigma}{\sqrt{2}\delta}\right)^2 = \left(\frac{\gamma_k\sigma}{\sqrt{2}}\right)^2, \quad \mathrm{x_k} = \gamma_k\delta, \quad (\gamma_k\delta)\,tg(\gamma_k\delta) = \frac{\alpha\delta}{\lambda} = Bi \qquad (6)$$

Here, q_s and q_v are the surface and volume heat densities respectively; δ - the thickness of the wall, λ - heat conductivity coefficient, α - heat transfer coefficient, ΔT_{max} - maximum temperature drop along the beam direction (z - direction), $T(0,\delta)$ - the maximum temperature drop between cooling surface and coolant and t_f - the lateral temperature drop along surface between points $r = 0$ and $r = \infty$.

This expression is an exact analytical solution of the two-dimensional equation of heat conduction. For a flat wall (Fig. 6) with the heat release density determined by equ. (1) it shows that the temperature rise across the wall at the maximum of the heat release density (~1.5 MW/m^3) is ~ 32 - 36 ^{0}C for stainless steel ($\delta = 1$ mm) and ~15 ^{0}C for aluminum alloy ($\delta = 5$ mm).

Efficient cooling of the beam windows will require a local water velocity of about 4-5 m/s, while the total flow needed to remove all of the heat dissipated in the irradiation insert is of the order of 8-10 m^3/h, which results in a flow velocity of about 0.5 m/s between the walls of the thimble. We are, therefore, contemplating to design a water feeding system that would take the water immediately down to the proton window region into a manifold with openings facing the beam windows of the beam stop insert and the irradiation insert. The water would then be directed as jets onto the two most heated walls and would generate a high velocity and turbulent flow at the beam windows. The concept is shown schematically in Fig. 7. While providing efficient window cooling, this concept also minimises the amount of wall material in the beam. The return flow would be cooling the outer wall of the irradiation insert.

If it proves feasible, this design would:

- avoid additional layers of structural materials and the corresponding beam widening;
- efficiently prevent the formation of a vapour boundary layer near the windows and ensure efficient heat exchange at the most strongly heated position;
- establish axial symmetry of window cooling;
- keep the total water flow rate at ~10 m^3/h as required to provide a reasonable thermal regime on the external surface of the liquid metal irradiation insert and the tungsten plates;
- be very space efficient, in line with the inner dimensions of the MHD pump, and the existing aluminum body;
- essentially retain the overall cylindrical symmetry of the insert;
- generate a relatively low flux of recoil protons to the samples;

3.3.3 Temperature control

Depending on the liquid metal used, the temperature should be kept constant at widely different levels. Since there will be a more or less constant heat source from the beam and the pump, this may require additional possibilities of heat input by heating elements located on the surface of the central cylinder. For Ga, Hg and PbBi (cf. 2.1) this may not be required, but may become a necessity if irradiations above 350°C shall be performed. For temperatures below that level it may be sufficient to vary the heat flow resistance across the double walled steel container by adjusting the gas pressure in the interspace to keep the temperature at the desired level. A detailed analysis is still pending, since it requires exact dimensions of the design. In any case, it should be possible to maintain the desired temperature level in the liquid metal while cooling the outer surface of the stainless steel container with moderately pressurised water only. Heat losses towards the top of the insert will have to be minimised by a system of baffles and a design with high heat flow resistance along the walls.

4. Ancillary equipment and handling procedures

Safe and relatively uncomplicated handling of the specimens and the irradiation insert after the end of the irradiation was an essential aspect in conceiving the whole system.

After irradiation the assembly (central cylinder and cassette) with the samples is lifted to allow the liquid metal to collect under the cassette in order to avoid damage of the samples if the metal solidifies (such as Pb-Bi) or to enable sealing its surface, if it stays liquid with a non-radioactive layer, for example Gallium[2] but possibly also simply water. This is done in hermetically sealed conditions (except for gas admission to fill the volume) by expanding the bellows at the top of the container. With the metal solidified or/and covered with an inert layer, the gas space can be vacuum dried and flushed to capture all volatile contamination in a filter system. This process can be assisted by activating the heater system on the central cylinder.

After unscrewing the top flange the central cylinder, together with the sample cassette, can then be pulled into a transfer cask with a shield gate at its bottom (Fig.8). This cask can be mounted on top of a smaller transport flask into which the cassette is lowered by means of the bar from which it is suspended (Fig. 5d). After detaching the bar from the cassette and closing the shielding gates of the transfer cask and the transport flask, the specimens are ready for shipment. Alternatively, the whole transport cask could be shipped to the hot cells and the specimens removed from it there (Fig. 8). In this case it is important that the cask dimensions meet the size requirements imposed by the hot cells.

In principle, a new cassette with a set of specimens can be loaded onto the support cylinder and inserted into the container for irradiation again. In this case the container would be positioned in such a way that the previous beam "window" is now located at an angular position out of the proton beam.

At the end of the container's service life, the metal in it can either be solidified by cooling (Pb, PbBi) or will be converted into a solid amalgam or compound in the case of Mercury. It will the be covered by an inert solid layer (PbBi) before being sent off to the radioactive waste disposal.

While the sample transport flask may be of the usual simple design of a shielded transport container - with provisions to fix the cassette in such a way that it can be detached from and attached to handling bar, the transfer cask should be able to serve a number of purposes:

- It should be possible to hook up the vacuum drying and flushing system to the transfer cask in order to remove residual contamination from any objects in it.

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[2] For temperatures ~ 30 – 40 ^{0}C, gallium has low solubility in mercury ~ 1 – 2 % and low vapour pressure10^{-5} - 10^{-4} Pa [26,27]. A layer of 2 - 4 cm can safely isolate mercury during handling operations above its surface.

- The cask should be suitable to handle the central cylinder with the sample cassette alone or the irradiation container or the whole assembly (Fig 8). In the latter two cases drying off the residues of cooling water must be possible.
- The cask must, of course, be of sufficient thickness to provide for safe working conditions in its vicinity in all situations. Probably a steel thickness of about 30 cm will be sufficient, which can be added to the outside of the cask according to actual needs. A gate valve with sufficient shielding capability and with provisions to solidify residues of liquid mercury when the inner part of the insert alone is handled should be provided at the bottom of the cask.
- The height of the cask should be sufficient to accommodate the irradiation container with the bellows expanded (Fig 8b). At least it should be possible to mount a suitable extension at its top.
- The transfer cask should allow to melt solidified metal in the bottom of an irradiation container
- It should allow encapsulation of remaining radioactive metal and its additional isolation before delivering to a storage after irradiation;
- The transfer cask should also be used to place a new irradiation insert in the beam stop.
- It must be possible to fix the irradiation container safely inside the cask also for long distance transport.

So, the transfer cask is a working place for the number of technological operations and must be designed with enough flexibility. The question, whether it should have its own hoist or whether the overhead crane can be used for all lifting operations has yet to be decided.

The system for vacuum drying, which is equipped with filters for holding back radioactive vapors, will decontaminate the ampoule surface and inner walls of the container. It should also be suitable to dry off the outer wall of the container which, during operation, are exposed to water. Mercury vapors shall be converted into solid amalgams or compounds.

5. Options

As noted above, the proposed installation can be deigned in such a way that it allows irradiation in a variety of different liquid metals and in a large temperature range, as well as under widely different load (internal tube pressure and power density) conditions. The dimensions mentioned in parts of the paper are rather tentative and chosen for the case where a peak power density in steel of 1.5 GW/m^3 is desired, which is a very high value. For lower power density the irradiated volume can be larger and so can be the dimensions of the test tubes. In this case it may even be possible to cut more or less "standard" test specimens from the tube walls and to examine them with usual tensile testing techniques. The necessary equipment, and relevant experience exist in IPPE and RIAR.

Standard practice in reactor irradiation is to fill the test tubes with the right amount of gas in such a way that the desired internal pressure is reached at the temperature of irradiation. In the case of proton irradiation heating is very non-uniform and most of the tube surface is at the average temperature of the surrounding liquid metal with only a hot spot at the position of the beam. In this case the uncertainty in temperature determination is, to a first approximation, proportional to the ratio of the part of the tube volume irradiated by the primary proton beam to the total gas volume in the tube. It may, therefore, be preferable to fill most of the volume inside the tube with liquid metal. This can either be the same material as the one used at the outside, or a different one whose behaviour towards the test tubes is known. Partial filling of the tube with liquid metal has three advantages: (1) it will enable a more definite temperature and hence gas pressure control; (2) it will enhance the neutron generation in the test volume and hence reproduce more closely the expected cascade-evaporation particle spectrum in a real target; (3) there is a smaller amount of gas in the volume, which results in less stored energy.

Hermetically sealed tubular samples partially filled by liquid metal and a gas filled cavity in the upper part (for pressure and temperature maintenance) would also allow chemical and spectroscopic analysis for spallation products in the liquid metal and in the gas .

With tubular specimens much longer than the beam dimensions, it will be possible to investigate ringlet samples, which were irradiated in different positions relative to the beam axis and, consequently, have different damage levels as well as different ratios of gas generation to defect production. For tubes irradiated in the geometrical shadow of the front tube, different effective proton energies and flux levels of cascade neutrons can be utilised.

If sodium (or another alkaline metal), is to be used as the liquid component, safe separation from the cooling water of the container is of prime importance. In this case the tubes can be filled with sodium, while their outside is surrounded by Pb-Bi, Ga or another easily melting alloy, serving as an additional barrier to separate the sodium from the water coolant. This will allow also safe use of sodium while , at the same time, keeping its amount at a minimum (~ 50 – 70 g).

In principle it should also be possible to carry out mechanical testing of samples in a liquid metal under irradiation and in situ straining (constant force, constant strain, or even cyclic) by using a technology similar to the one implemented a PIREX at PSI [28] and taking advantage of the fact that the sample cassette is only suspended from the central bar and that this assembly could be replaced by a differently designed one.

6. Conclusions

The above considerations show that the it is possible to realise a facility at the beam stop of the Moscow Meson Factory which, even at the current performance levels of the accelerator would allow important irradiation experiments with regards to liquid metal-solid metal interactions. Most of the technical solutions of this concept have been realised elsewhere in the past and calculations show that they can be adopted to the prevailing conditions. The installation as conceived is rather flexible and may be adopted in order to operate with different coolant or spallation target metals. Dimensions and shapes of samples can be varied, as can be temperature and pressure (mechanical load). Furthermore, the system would be rather cost effective, since it is possible to use existing technologies and equipment of research laboratories at IPPE, Kurtchatov

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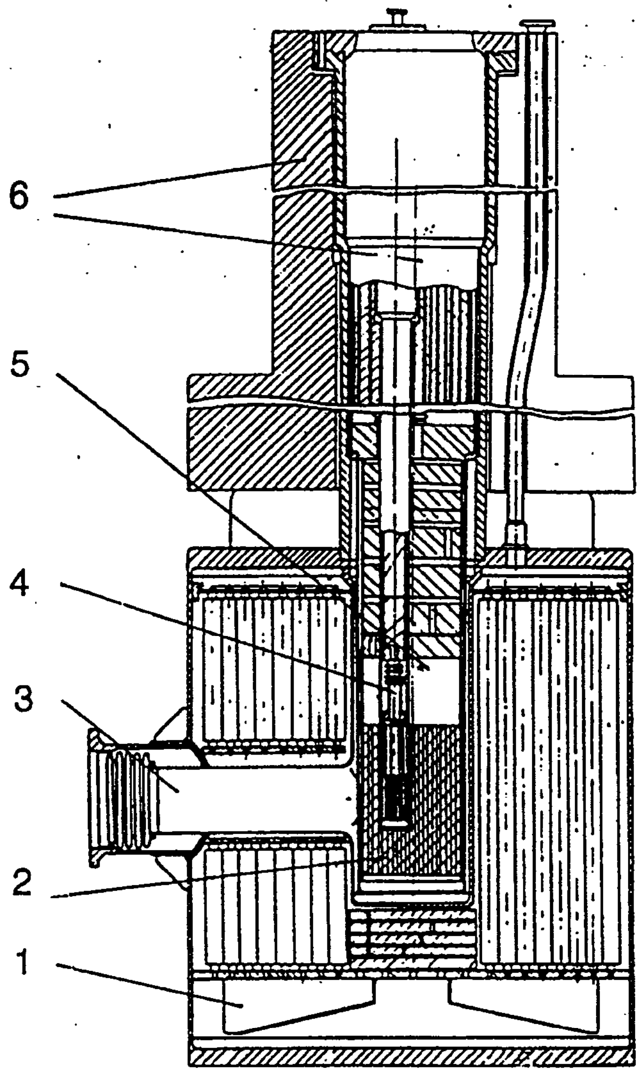
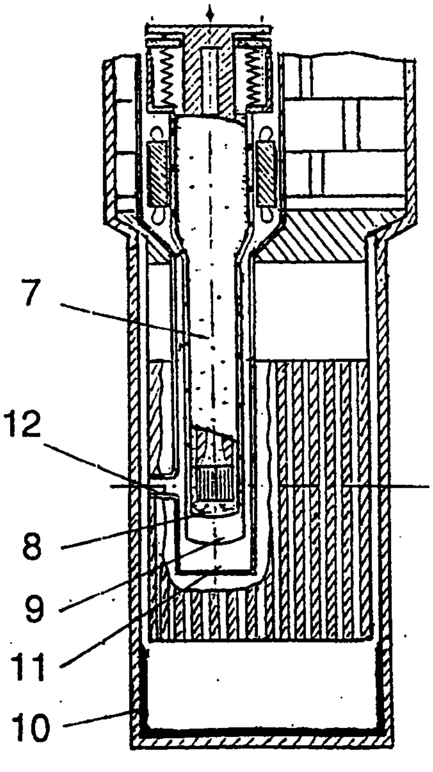


Figure 1a: Sketch of the present beam stop at the MMF:

1 water cooled shielding.
2 beam stop insert made of tungsten plates.
3 proton beam channel.
4 irradiation insert in thimble.
5 aluminium vessel.
6 removable top shield (steel plugs).

Figure 1b: Sketch of the proposed LM-irradiation insert that would replace the present irradiation insert, requiring only minor modifications to the tungsten plate assembly:

7 liquid metal container.
8 liquid metal
9 outer container of stainless steel with gas atmosphere.
10 Al_2O_3 cover of the bottom part of the aluminium vessel for corrosion protection in case of a LM leak.
11 receptacle for irradiation insert with water filled catcher volume.
12 jet forming manifold for window cooling



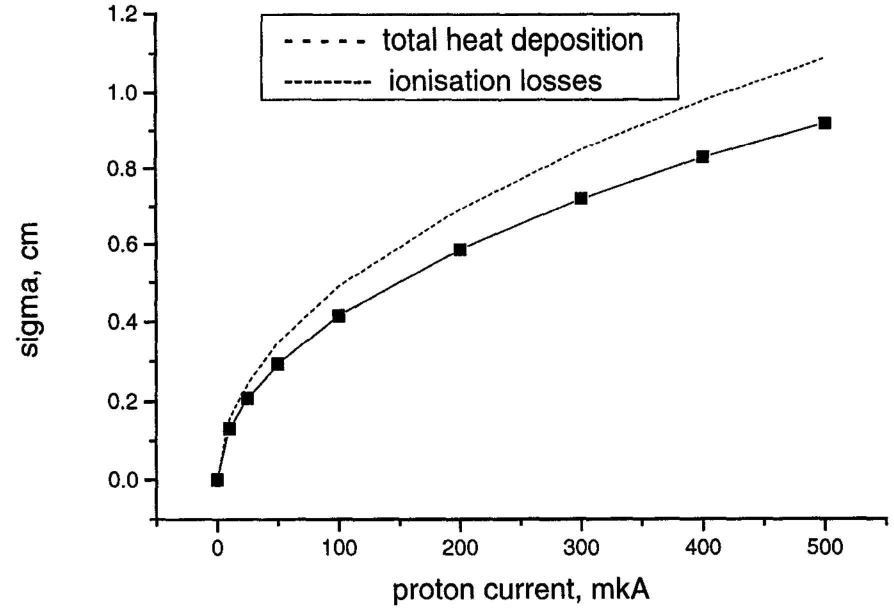


Figure 2: Dependence of the standard deviation σ of a beam with Gaussian intensity profile on the proton current for a stainless steel sample with required maximum heat deposition of 1.5 kW/cm^3. The solid line corresponds to ionisation losses only, the dashed line is the total heat deposition.

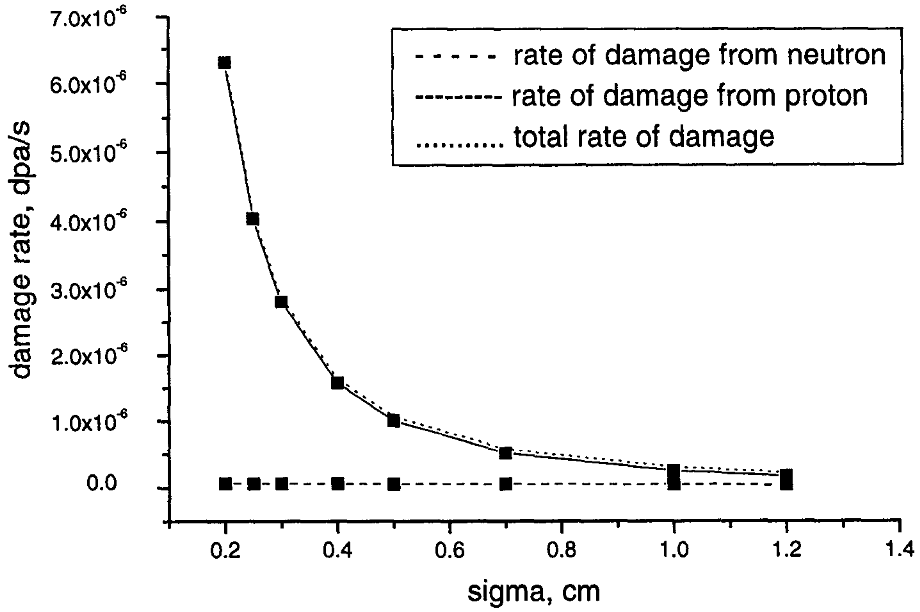


Figure 3: Estimated radiation damage rate due to the proton beam (450 MeV) and the spallation neutron flux as a function of beam width at 100 μA

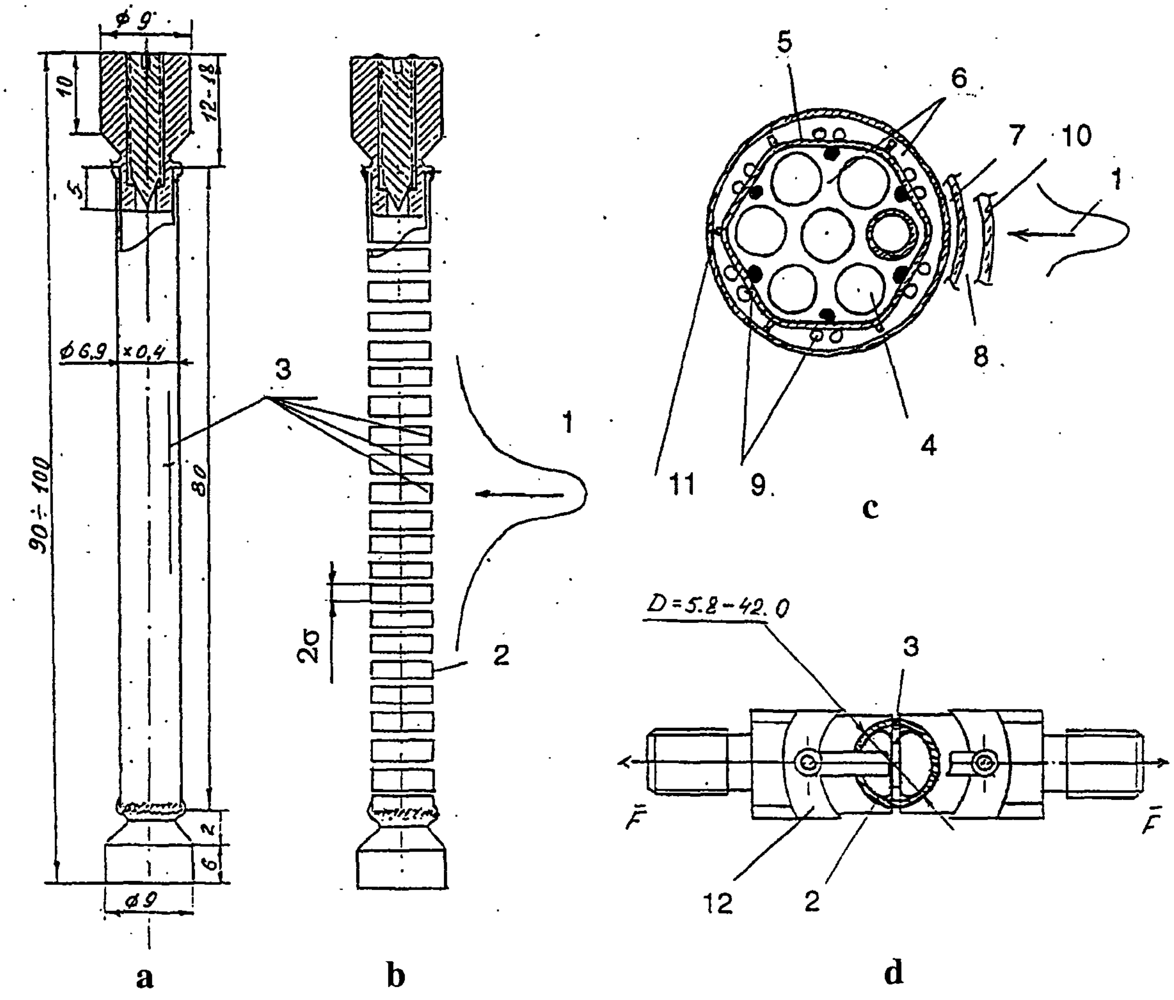
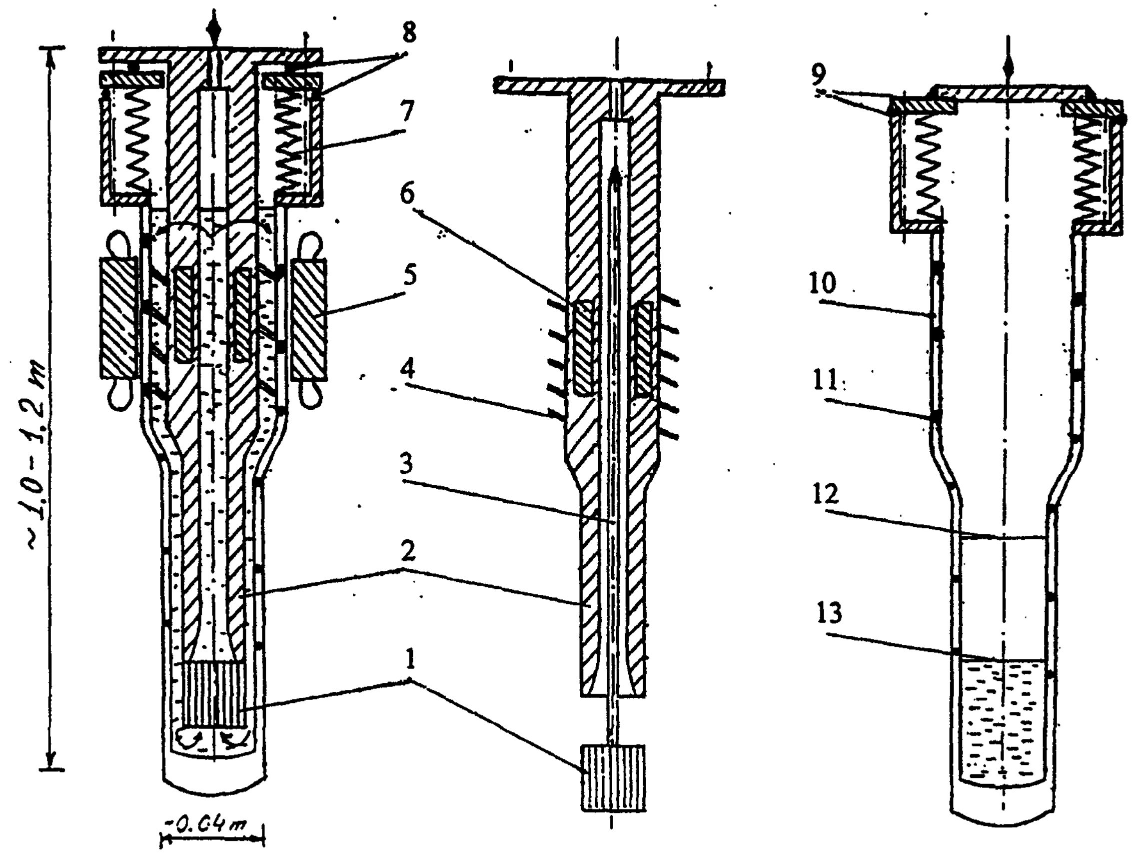


Figure 4: Scheme of samples:
a - tubular sample with sealing plug at the top
b - sample cut up into rings for post irradiation examination
c - specimen cassette with 7 tubular samples
d - typical ring holder for mechanical test of ring samples

1	proton beam
2	sample ring
3	mark
4	tubular sample in cassette
5	cassette body (non stress samples)
6	liquid metal (Hg or Pb-Bi) under the temperature of 150-250°C
7	He or Ar thermal barrier
8	water coolant
9	thermocouples in the protective covering and displacers
10	outside body
11	spacers
12	clamps on testing device



a b c

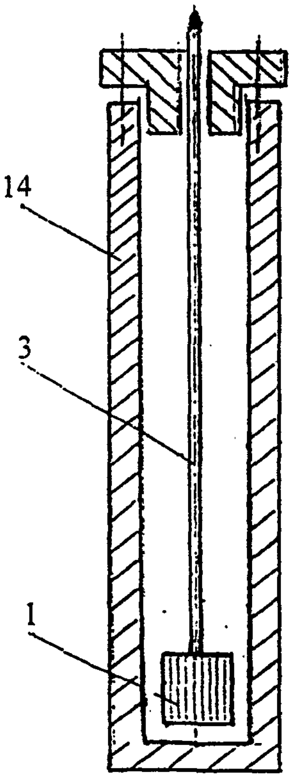
Figure 5: Sketch of the assembly and the main elements of the LM irradiation insert:

a - assembled insert;

b - flow guide and displacement body with specimen cassette suspended from its support bar and pushed down from the flow guide

c - liquid metal irradiation hull ready for shipment to disposal: the liquid metal has been solidified and a top plate welded in place for permanent sealing;

d - specimen cassette in transport flask.



d

1 cassette with tubular specimen
2 cylindrical flow guide and liquid metal displacement body
3 cassette support bar (holding diagnostics and supply leads)
4 helical flow guide for pumping
5 rotating field EM-pump
6 low permeation steel core to increase EM-pump efficiency
7 bellows for concealed lifting of sample cassette
8 seals
9 welds
10 double walled stainless steel hull
11 spacers
12 level after mercury has been solidified
13 liquid metal level before solidification

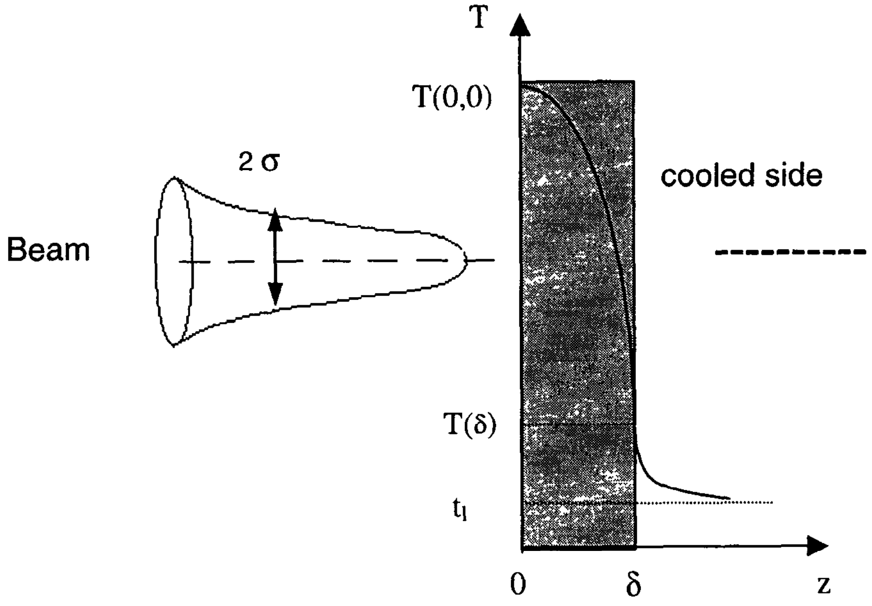


Figure 6: Configuration assumed for calculating the temperature gradient in the walls.

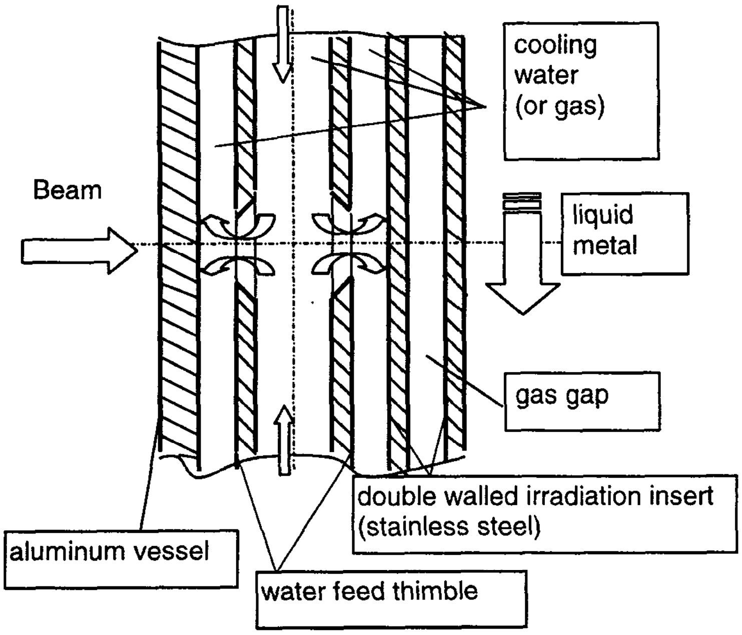


Figure 7: The concept of jet cooling of the beam windows.

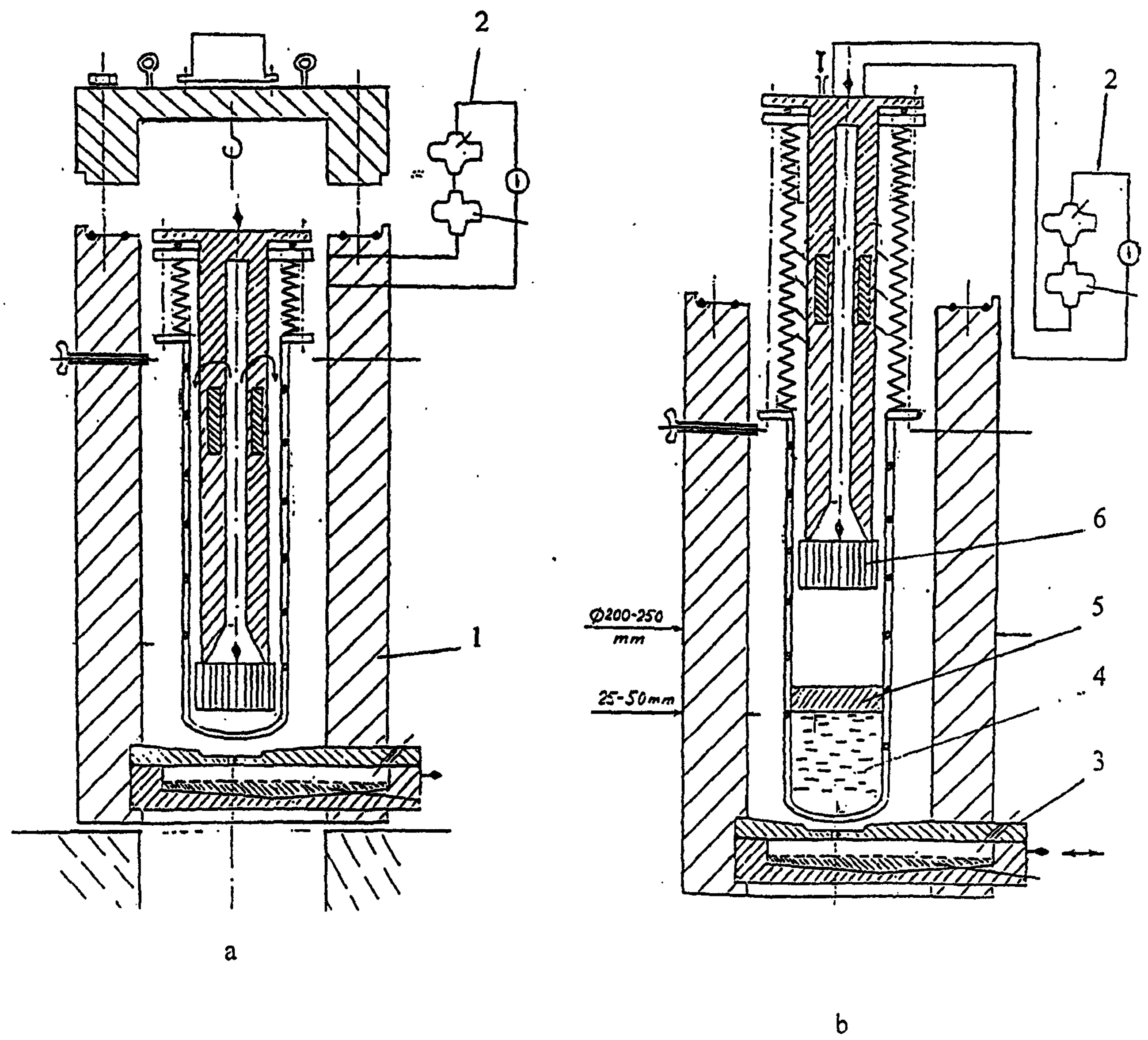


Figure 8: Sketch of additional equipment and possible alternative removal procedures
a - LM-insertion in the transfer container and cleaning of outside surface
b - the cleaning of holder with samples

1 transfer container
2 vacuum drying system
3 removable bottom with Pb or Cu
4 LM level after lifting of the samples
5 Ga-plug (~3 cm)
6 cassette with samples